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MARINE GEOLOGY

Continental Slopes of the West Africa Region: A Unique Treasure of Hydrocarbons

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Abstract—The West African region embraces a number of coastal sedimentary basins, which continued in deep-water areas of the Atlantic Ocean. It includes the following oil-and-gas-bearing basins: the Gulf of Guinea, the Kwanza–Cameroonian, and the Namibian. The sedimentary cover of the basins of this passive margin is represented by Mesozoic–Cenozoic deposits. The composition of sediments accumulated in them is quite specific and surprisingly units over the vast areas. The tectonic structure of the majority of the continental margins of West Africa makes possible to refer them to the margins of epiplatform orogenic belts. The existence of two systems of linear troughs—internal and external—on the passive margins at the early stages of continent–ocean transition zones relates deep-water hydrocarbon deposits to internal troughs filled by younger sediments: the alluvial fans of submarine rivers and landslide fronts with prograde formations (turbidites, debris flows, etc.). Late Cretaceous and Middle Paleogene clay formations played the role of source beds in the region, so-called "black clays." An analysis of over 200 hydrocarbon fields, mainly petroleum, discovered in the past 10–15 years in the region revealed a clear tendency of these fields occurring in a productive zone of oil pools extending in a sea depth interval of 400–3000 m on the continental slope and possibly to 4000 m at the continental rise. Moreover, all discovered fields have been estimated in terms of reserves from large to giant. It is also noteworthy that within the shallow of this region, which includes the shelf and the coastal plain, only a number of small, insignificant oil and gas pays have been discovered. The main of oil and gas bearing potential prospects are related to deposits in the middle and lower parts of the continental slope and possibly adjacent areas of the continental rise. In the long term, the drilling objectives will be both postsalt and presalt deep-water oil-and-gas fields.

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The deep-water area of the World Ocean belongs to the small number of regions on our planet associated with prospecting for large hydrocarbon reserves in the 21st century. Continental slopes and rises are one of the main morphostructural elements of the World Ocean occurring in its deep-water areas. Therefore, one of the primary tasks in studying the margins of the West Africa is to estimate the potential hydrocarbon resources of the continental slopes with existing structures and the geological history of their formation.

Within the Atlantic system of West African basins, a number of sedimentary basins are distinguished from north to south: the Gulf of Guinea, the Kwanza–Cameroonian, and the Namibian (Fig. 1) These basins are a perfect example of high potential discoveries of large hydrocarbon reserves in continental slopes region.

The main processes determining development of slopes throughout their long history were subsidence and sediment accumulation. Thanks to irregular subsidence of individual blocks of the crust during the breakup of the ancient continents, the continental slopes evolved with a stepped structure. A kind of depressions–pockets arising at the boundaries between irregular sinking blocks, transformed with time into semigrabens and grabens, playing a role of trap for sediments, which transported from the shelf or subsided from the water column. Geophysics has recorded relics of these structures as troughs buried beneath a younger sedimentary cover.

The sedimentary cover of the basins of the passive margin of West Africa is represented by Mesozoic–Cenozoic deposits. On the Precambrian basement, at the base of the sedimentary cover, is a rift complex, which formed during the breakup stage of the ancient continental crust. Continental rifts on which there was a broken of the ancient supercontinents of Pangaea and Gondwana at its greatest length intersected deep-seated regions of the ancient continents.

The schematic correlation of the stratigraphic sections of this region illustrates that the composition of

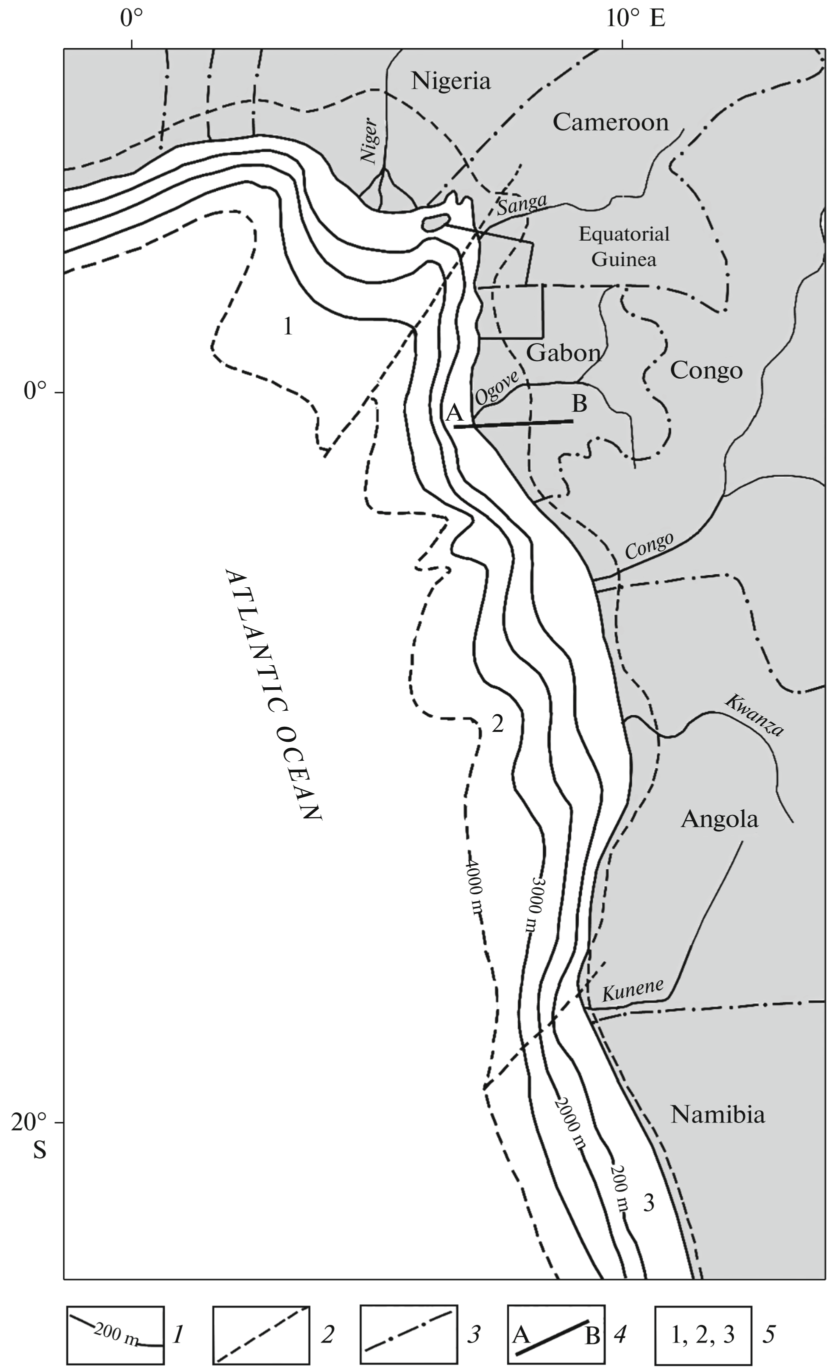

Fig. 1. Schematic map of sedimentary basins of West African continental margin. Compiled by A. Zabanbark and L.I. Lobkovsky. (*1*) Water depth isobaths, m; (*2*) boundaries of sedimentary basins (established and assumed); (*3*) state borders; (*4*) line of A–B profile in Fig. 3; (*5*) numerals on map are oil-and-gas-bearing basins: (1) Gulf of Guinea; (2) Kwanza–Cameroonian; (3) Namibian.

sediments accumulated in them was quite specific and surprisingly uniform over vast areas (Fig. 2).

The tectonic structure and developmental history of the majority of the continental margins of Africa and the Atlantic Ocean make it possible to refer them to the margins of epiplatform orogenic belts, the specific features of which are an erosional coast, a narrow shelf, and a quite gently continental slope covered with landslide deposits and frequently complicated by salt diapirs and salts of the Loeme and Ezanga formations (Kwanza–Cameroon Basin) (Fig. 3). The main mechanism for the formation of structural traps in the region is halokinesis. The movement of salt that began here in the Jurassic continues to this day [14, 23]. It

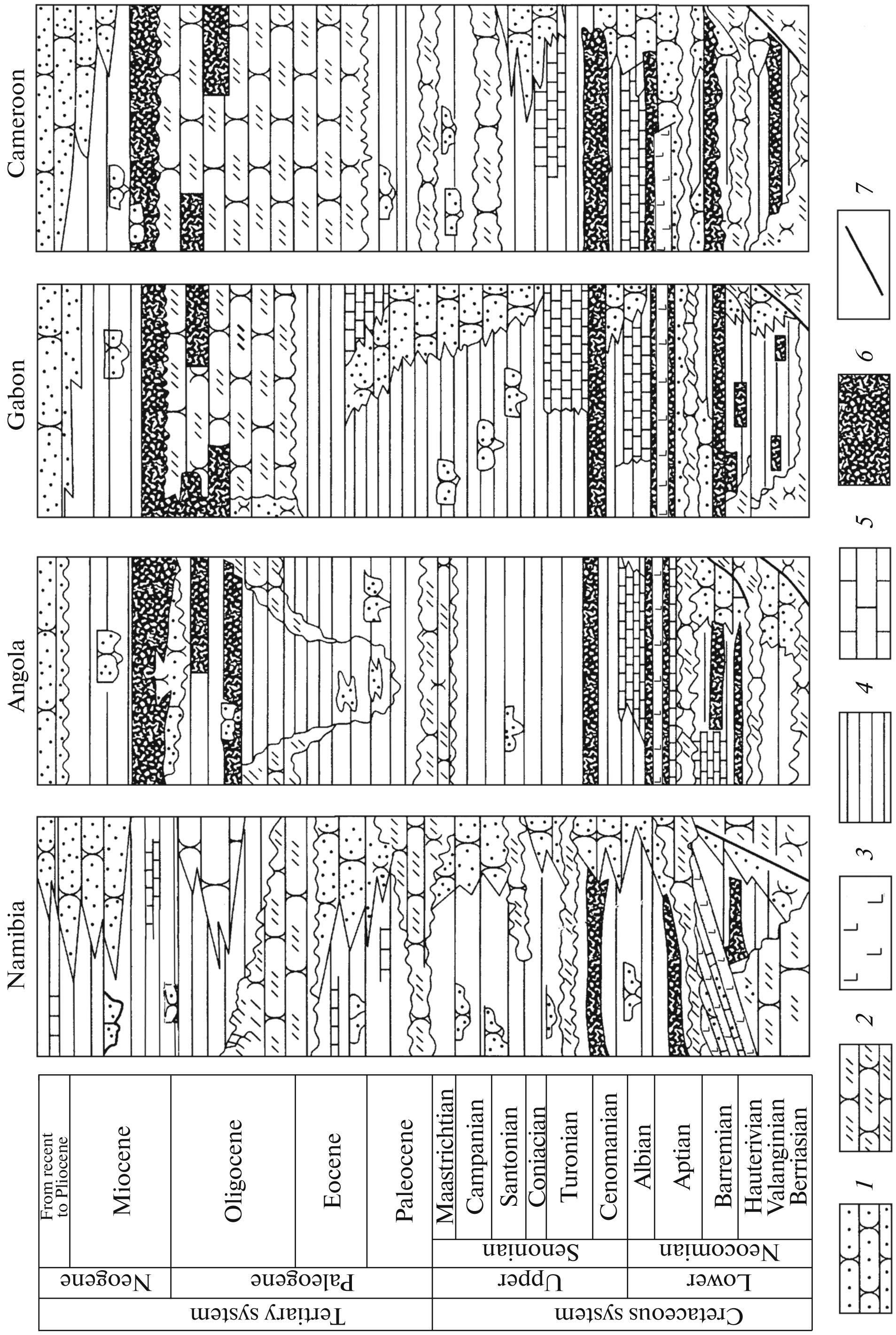

Fig. 2. Schematic correlation of the stratigraphic sequences of West African continental margin. Compiled by A. Zabanbark and L.I. Lobkovsky from materials [1, 2, 14, 15]. (*1*) Sandstone; (*2*) siltstone; (*3*) salts; (*4*) clay shale; (*5*) limestone; (*6*) oil-and-gas-bearing strata; (*7*) faults.

has been established that the growth of salt domes began as a result of salt flow southward under the loading of overlying deposits. The dynamic action of mobile salts on deep-water turbidite sediments led to the formation of salt dome structures with high-quality reservoirs. As a result, anticlinal traps formed on the flanks of salt traps. Similar traps have been discovered in seismic survey operations, and there are a great number of them along the West African margin. Most of them have large areas from 100 to 150 km^2.

At earlier stages of studying continent–ocean transition zones, two linear systems of troughs were estab-

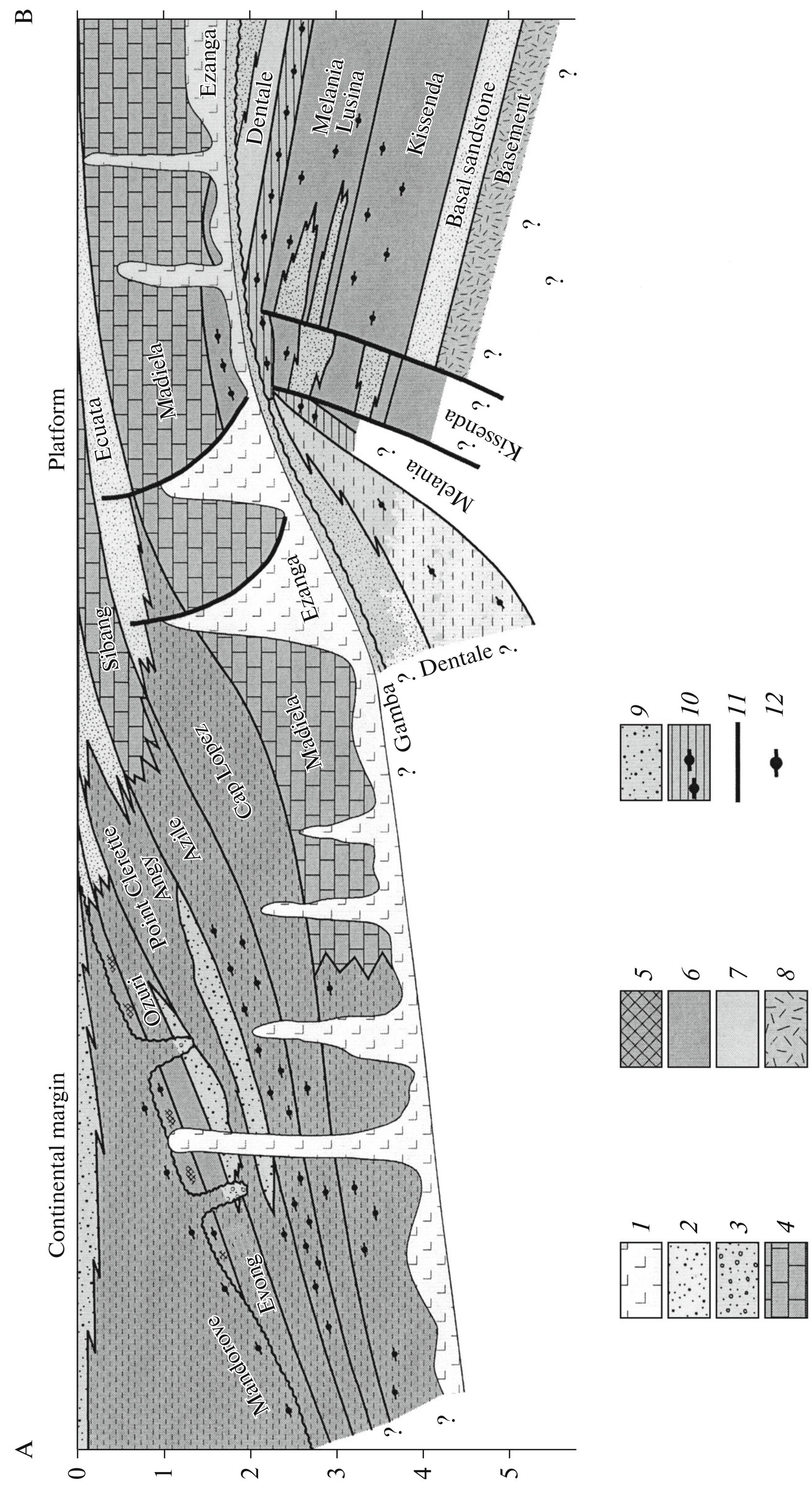

Fig. 3. Schematic geological profile on Gabon [8]. Line of profile in Fig. 1. (*1*) Salt; (*2*) limestone; (*3*) conglomerate; (*4*) limestone; (*5*) silicified clay shale; (*6*) clay shale; (*7*) aleurite; (*8*) basement rocks; (*9*) possible reservoir rocks; (*10*) Melania formation–lacustrine–continental crustal rocks; (*11*) faults; (*12*) source rocks.

lished on the passive margins [3]: a system of internal troughs traceable in the belt of the coastal plain and shallow-water shelf, and a system of external troughs that extend along the lower half of the continental slope and adjacent regions of the continental rise. The troughs of the first type are grabens and semigrabens of rift laying filled with ancient sediment complexes (at least the lower and middle parts of the section). On the contrary, the external troughs contain more later sediments and correspond to the development stage of the proper continental margin. The majority of sediment sequences here consist of young sediments: submarine alluvial fans from the Niger, Ogove, Congo, Kwanza, and Cunene rivers and landslide fronts with prograde units (turbidites, debris flows, etc.). Based on this, recent prospecting works have concentrated precisely on deep-water areas, since the reservoirs occurring in Tertiary and Upper Cretaceous rocks are significantly better in quality than the reservoirs of Lower Cretaceous deposits near the coast and shallow-water areas. Thus, in the deep-water zone from Cameroon, Gabon, and Congo to Angola and Namibia, more than 200 large, mainly petroleum fields have been discovered for 10–15 years, which has made it possible to significantly (almost twofold) increase the proven hydrocarbon reserves in most of the mentioned countries. The indicated accumulations are mainly associated with turbidites and terrigenous deposits and close to them in genesis from submarine fans (deep-water fans) of Aptian–Cenomanian and Oligocene–Miocene age.

In the deep-water basins of the Atlantic margin of West Africa, reservoir horizons (Oligocene–Miocene) consisting of sandstone and aleurite are characterized by high porosity (28–30%) and permeability indices (3–4 darcys). In the oil-and-gas-bearing complex, with a thickness of 223 to 300 m, a few productive horizons are usually distinguished, and the height of the hydrocarbon pay can reach 94 and even 100 m. The majority of accumulations are associated with stratigraphic and combination traps. It is supposed that the source beds in this immense region were clay sequences of Early Cretaceous, Late Cretaceous, and Middle Paleogene age, so-called "black clays," which accumulated in deep-water settings with limited oxygen availability. This is a quite diverse group of deposits unified by one particular feature: enrichment in organic matter, which is responsible for their black color. Research conducted in recent years has shown that not only the mineral composition of black clays, but also the composition of their organic part, differs sharply in these, uniform at first glance, sediments [4, 5]. Black clays were the most widespread at the end of the Early Cretaceous and beginning of the Late Cretaceous (Aptian–Albian and Cenomanian–Turonian). The C_{org} content varies layerwise in black clay sections from 1–2 to 32%. Many variations, which were founded by drilling in core samples from the distal parts of continental rises turned out to be turbidites upon careful examination. Thus, Lower Cretaceous source rocks of the Bukomasi formation contain type I kerogen and 5–20% total organic carbon (TOC) [8].

Particular importance are areas where continental rifts and aulacogens extend toward the ocean. Continental slopes at such margins were formed by the thickest terrigenous sediment complexes. They are associated with the estuaries of large river arteries that discharged clastic material mobilized on land into the ocean over many millions of years. Submarine river deltas located on the shelf transited on the continental slope into a submarine fan, moving into the ocean, gradually increasing the continental margin. A slope formed in such a way is prograde [1]. Frequently, within the limits of such slopes the Earth's largest sediment complexes form, the thickness of which can exceed 15–20 km; the Gulf of Guinea and Bay of Bengal are such sedimentary basins. The most striking example is the margin of Africa in the Gulf of Guinea and south of it, where such large rivers as the Niger, Ogove, Congo, Kwanza, and Cunene discharge their waters. The drops of ocean level in the Early and Late (Messinian) Miocene, which were quite significant, although conceded of the Middle Oligocene, were accompanied by the movement of large and small river deltas onto the shelf [1]. In addition, the process took place of the background tectonic activation, which captured many areas of Africa. All of this led to transport of a significant amount of terrigenous clastic and clayey material onto the continental shelf, slope, and rise. These terrigenous delta and coastal–marine formations are natural reservoirs for hydrocarbon pays, and their presence confirms the prospects of the considered region. Analysis of currently known oil and gas fields shows that ancient delta complexes of the continental margins of West Africa regionaly is oil and gas bearing not only due to good reservoir horizons, but also mainly to the optimal ratio of natural reservoirs, source rocks, and screens (seals). The thing is that the absence of suitable overlying caprock—horizons and clay packets developed on a regional scale—is frequently a factor limiting the possibilities for large oil and gas accumulations to form in some areas of the present-day margins, e.g., on the Atlantic periphery of the United States.

An analysis of over 200 hydrocarbon fields mainly petroleum, discovered in the mentioned period in the deep-water part of the West African margin, revealed a clear tendency of these fields occurring in a productive zone of oil pays extending in a sea depth interval of 400–3000 m on the continental slope and possibly to 4000 m on the continental rise (Table 1). However, this productive belt most likely does not break off after the Gulf of Guinea Basin, but continues farther north into areas of the continental slope and rise of Senegal, Mauritania, and Morocco. A number of new large oil and gas fields discovered here in the last 3–5 years confirms this. Moreover, all fields within this productive belt are estimated to be from large to giant in terms

Table 1. Characteristics of certain hydrocarbon fields of deep-water part of Angola

Name of deposits	Discovery date	Sea depth, m	Fluid type	Reservoir age	Oil reserves, million t
Miranda	2006	2436	Oil		–
Rosa	1998	1350	Oil	Miocene/Oligocene	137
Girassol	1996	1350–1500	Oil	Miocene/Oligocene	126–137
Bicuar	2012	1680	Oil		21–42
Colorau-1	2006	1700	Oil	Oligocene	
Miramba North	2007	1170–1300	Oil/Gas	Miocene/Oligocene	11.7
Xikomba	1999	1200–2000	Oil	Miocene/Oligocene	13.7
Kizomba A	1998	1350	Oil	Miocene/Oligocene	56.6
Kizomba B	1998	1350	Oil	Miocene/Oligocene	
Lira	2011	1000–15000	Gas/Condensates	Miocene	
Saxi	2001	800	Oil	Miocene/Oligocene	
Batuque	2001	800	Oil	Miocene/Oligocene	
Azurite	2005	1400	Oil	Miocene	
Mpungi	2010	1000–1500	Oil	Miocene	370
MpungiNorth	2013	1000–1500	Oil	Miocene	
Vandumbu	2013	1000–1500	Oil	Miocene	
Cinguvu	2010	1000–1500	Oil	Miocene	
Sangos	2008	1000–1500	Oil	Miocene	
Plutonio	2000	1200–1500	Oil	Miocene/Oligocene	103
Galio	2000	1200–1500	Oil	Miocene/Oligocene	
Cromio	2000	1200–1500	Oil	Miocene/Oligocene	
Paladio	2000	1200–1500	Oil	Miocene/Oligocene	
Cobalto	2001	1200–1500	Oil	Miocene/Oligocene	
Kaombo	2014	1400–2000	Oil/Gas	Miocene/Oligocene	137
Orchigufu	2014	1337–1421	Oil	Miocene/Oligocene	41.4
Nianzi	2004	820–1070	Oil/Gas	Miocene/Oligocene	10
Dahlia	1997	1200–1500	Oil	Miocene	137–170
Camilia	1999	1200–1500	Oil	Miocene	
Cravo	1999	1400	Oil/Gas	Miocene/Oligocene	23.4
Lirio	1998	1400	Oil/Gas	Miocene/Oligocene	21–75.4
Orchidea	1999	1400	Oil/Gas	Miocene/Oligocene	25.1
Violeta	2001	1400	Oil/Gas	Miocene/Oligocene	
Kuito	1997	350–400	Oil	Cretace/Tertiary	137
Kakosha	2001	750–1350	Oil	Miocene	26.1
Bavuka	2001	800–1350	Oil	Miocene	
Mondo South	2001	800–1350	Oil/Gas	Miocene/Oligocene	
Dikanza	1998	1000	Oil	Miocene/Oligocene	137
Cassiopee East	2007	2000	Oil	Miocene	
Orca	2014	1800	Oil	Cretaceous, Aptian	100
Lontra	2013	1750	Gas/Condensates	Cretaceous	60–110
Azul	2012	923	Oil	Cretaceous, Aptian	
Cameia	2012	1680	Oil/Gas	Cretaceous, Aptian	55
Kissanje	1998	1000–1370	Oil/Gas	Miocene/Oligocene	137
Dikanza	1998	1000	Oil/Gas	Miocene/Oligocene	
Sessio	2003	1500	Oil	Miocene/Oligocene	41.1
Shumbo	2003	1620	Oil	Miocene/Oligocene	

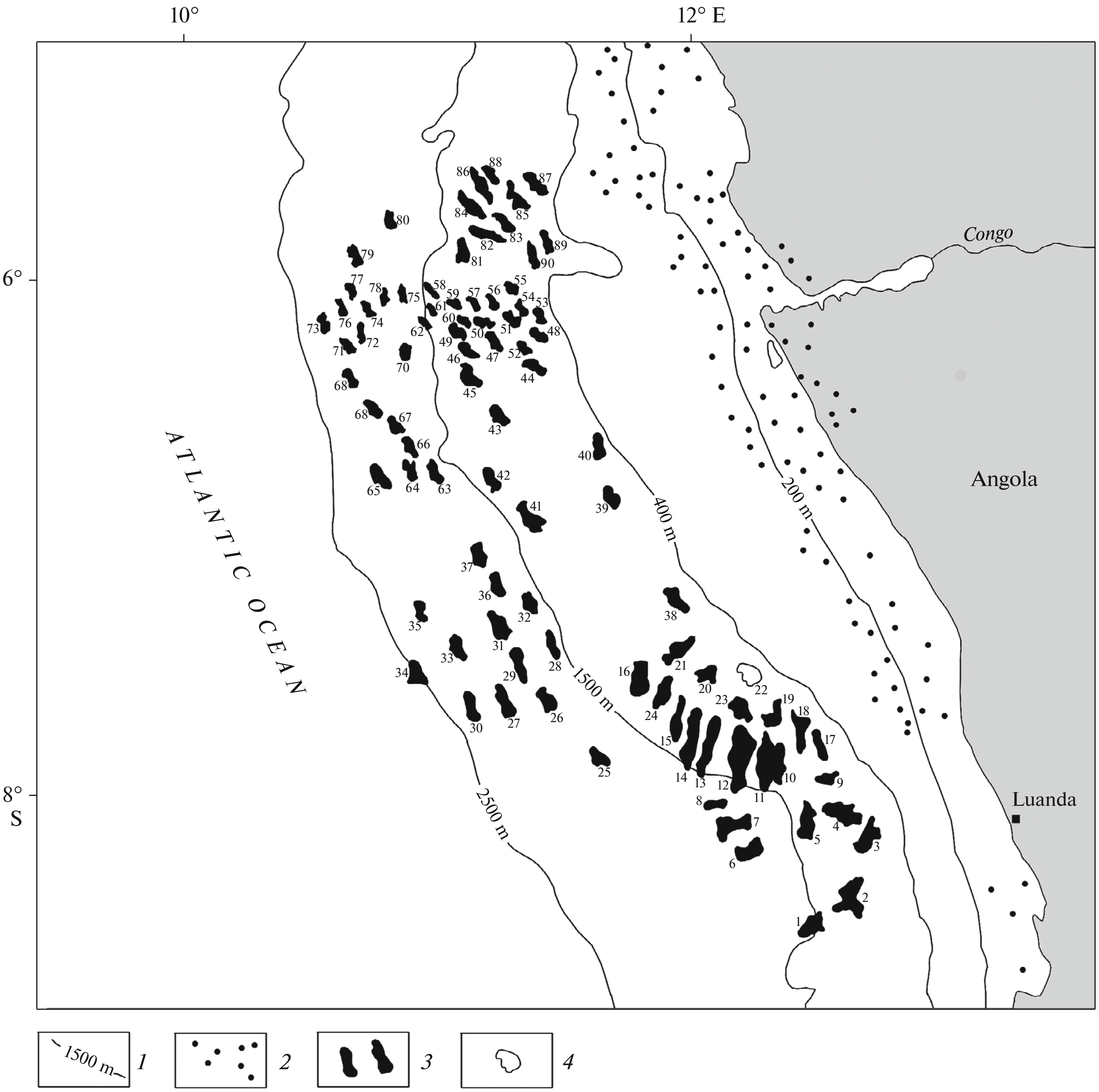

Fig. 4. Schematic map of oil-and-gas-bearing Angolan continental margin. Compiled by A. Zabanbark and L.I. Lobkovsky from materials [7, 9, 10, 13, 16, 17, 22]. (*1*) Water depth isobaths, m; (*2*) coastal plain and shallow-water hydrocarbon fields; (*3*) petroleum fields on continental slope; (*4*) gas fields on continental slope. Numbers on the map are fields names: (1) Cesio; (2) Plutonio; (3) Paladio; (4) Cromio; (5) Platina; (6) Chumbo; (7) Galio; (8) Cobalto; (9) Acacia; (10) Camelia; (11) Dahlia; (12) Girassol; (13) Rosa 1; (14) Rosa 2; (15) Orchidea; (16) Lirio; (17) Zina; (18) Perpetua; (19) Tulipa; (20) Anturio, (21) Violeta, (22) Magadira gas, (23) Jasmine, (24) Cravo; (25) Calulu; (26) Salsa; (27) Mostarda; (26) Canela; (29) Gengibre; (30) Louro; (31) Gindungo; (32) Cola; (33) Caril; (34) Manjerikao; (35) Colorau; (36) Cominhos; (37) Alho; (39) Bengo; (40) Longa; (41) Chissonga; (42) M'Bridge; (43) Tchihumba; (44) Blumbumba; (45) Kizomba D; (46) Marimba; (47) Kissanger; (48) Saxi; (49) Kizomba A; (50) Dikanza; (51) Kizomba C; (52) Kizomba B; (53) Mondo; (54) Bavuka; (55) M'Pungi; (56) Hungo; (57) Chocalho; (58) Xikomba; (59) Cinguvu; (60) Sangos; (61) Ginguvu; (62) N'Gom; (63) Astraea; (64) Palace; (65) Dione; (66) Oberon; (67) Juno; (68) Tebe, (69) Mirando; (70) Ceres; (71) Titania; (72) Portia; (73) Terra; (74) Plutao; (75) Saturno; (76) Leda; (77) Marte; (78) Venus; (79) Pegase; (80) Andromede; (81) Negage; (82) Landana; (83) Tombaco; (84) Lobito; (85) Belize; (86) Benguela; (87) Kuito; (88) Nianzi; (89) Tômbua, (90) Ducapa.

of hydrocarbon reserves. It is also noteworthy that within the continental shallows of this region, which includes the shelf and the coastal plain, where exploration have been carried out over many decades, only a number of small, insignificant oil and gas pays have been discovered. It should also be noted that almost of the fields are located in postsalt deposits. Only over the last 2–3 years the drilling in presalt sediments—in

Table 2. Characteristics of certain oil and gas fields in deep-water parts of Nigeria

Fields name	Discovery date	Sea depth, m	Fluid type	Reservoir age	HC reserves	
					oil, million t	gas, billion m^3
Bosi	1996	1400	Oil/Gas	Miocene, Cretaceous	21.5	
Abo	1997	500–780	Oil/Gas	Miocene, Cretaceous	12–14	
Erha	1999	1000–1900	Oil	Miocene, Cretaceous	68.5	
Erha North	2002	900	Oil	Miocene	24.3	
Bonga	1996	1000–1400	Oil/Gas	Miocene	82–94.4	
Bonga SW	2001	1245–1344	Oil/Gas	Miocene	82.2	
Aparo	2001	1344	Oil/Gas	Miocene		
Agbami	1998	1450–1500	Oil/Gas		109.6	
Egina	2003	1600–1750	Oil	Miocene	75.35	
Akpo	2000	1360–1500	Oil/Gas	Miocene	85	29
Usan	2002	750–900	Oil	Miocene	82.2	
Nsiko	2003	1750–1812	Oil	Miocene		
Bolia	2001	1100–1380	Gas/Oil			21.8
Ikia	1999	1400	Oil/Gas	Miocene-Oligocene		
Uge	2006	1263	Oil/Gas			
Doro	1999	1280	Oil	Miocene–Oligocene		
NNWA-Doro	1999	1200	Gas	Pliocene, Miocene		235.2
Hota	2001	1000	Oil/Gas	Pliocene, Miocene		
Bonga NW	2007	1250	Oil/Gas	Miocene		
Okpok	2006	500	Oil	Miocene–Oligocene		
Adje	1999	900–1000	Oil/Gas	Turon–Cenn–Alb	37.4	
Oyo	2006	310–500	Oil/Gas	Pliocene–Miocene		

analogy with the Brazilian margin, where a number of giant fields have been found in presalt Aptian deposits, e.g., the Lula at a water depth of 2000 m, with reserves of 1.2 billion t of oil-revealed giant petroleum fields on the slope within the Angolan margin, e.g., the Cameia, Lontra, and Orca fields, with reserves of 55–100 million t in Aptian rocks at a water depth of 1680–1800 m (Table 1).

As an example, we should mention the continental slope of Angola, where at depths from 400 to 2500 m more than 115 large fields have been discovered in the last 10–15 years (Table 1, Fig. 4). Three-fourths of the production oil in Angola is concentrated in the deposits of two productive complexes of Aptian–Cenomanian and Oligocene–Miocene age, consisting of deep-water deposits represented by the reservoirs of the Molembo Formation (Oligocene–Miocene) mainly in turbidite or closein genesis terrigenous units of submarine alluvial fans, as well as in reservoirs of the Pinda and Catumbela formations (Aptian–Cenomanian) in carbonate sediments. Total oil and gas reserves in Angola as of the beginning of 2017 were estimated, respectively, at 1.2 billion t and 304.6 billion m^3; oil production at this time was 90 million t.

No less interesting are the continental slopes of the Nigerian margin located deep in the Gulf of Guinea and associated with an ancient stable subsidence zone. This is a classic example of a continental rift margin, in which are productive mainly terrigenous, alluvial, and coastal–marine deposits of gravity material flows, including turbidites and landslide sediment masses. It is associated with the prograde area of the passive margin, where a thick accumulative body is formed, consisting of terrigenous material, transported here by the large artery of the Niger River. In the area of the delta, three sediment complexes are distinguished, differing not so much in age as by facies composition. These are the Akata, Benin, and Agbada formations. The main productive complex is the Agbada formation, represented by sandstone alternating with clay. The age of the deposits in most areas is Eocene–Pleistocene (for the Benin series, Oligocene–Pleistocene). However, it varies from north to south: in the ground northeastern parts of the delta, Agdaba sandstone and clay are of Paleogene age, then how in the submarine part of the

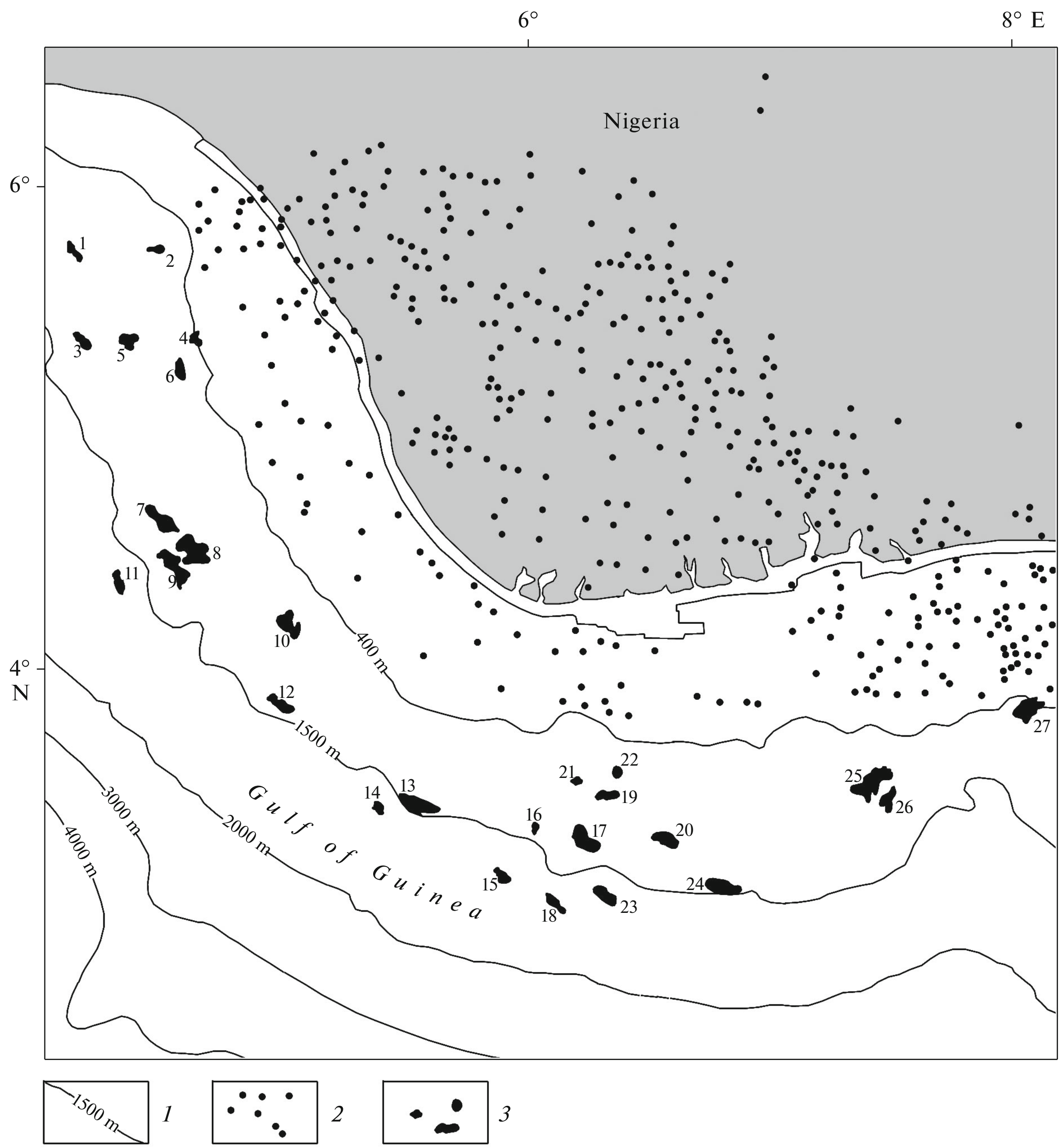

Fig. 5. Schematic map of oil-and-gas-bearing of Nigerian continental margin. Compiled by A. Zabanbark and L.I. Lobkovsky from materials [6, 11, 12, 18–21]. (*1*) Water depth isobaths, m; (*2*) coastal plain and shallow-water hydrocarbon fields; (*3*) petroleum fields on continental slope. Numbers on the map, names of fields. (1) Adje; (2) Abo; (3) Bosi; (4) Erha North; (5) Erha; (6) Oyo; (7) Bonga NW, (8) Bonga; (9) Bonga SW; (10) Aparo; (11) Nsiko; (12) Uge; (13) Agambi; (14) Ikija; (15) Etan; (16) Bilah; (17) NNWA, Doro; (18) Lura, (19) Bolia; (20) Hota; (21) Sehki; (22) N'Golo; (23) Egina; (24) Akpo; (25) Usan; (26) Ukot; (27) Okpok.

delta and within the alluvial fan, they are formed in the Pliocene–Pleistocene. In the ocean depth range from 400 to 2000 m, on the continental slope of Nigeria, more than 30 large hydrocarbon fields have been discovered in the last 10–15 years (Table 2, Fig. 5). Cretaceous units encountered in the pools extending to the north are also promising. So far as the technology of exploration and development of oil and gas fields in deep-water regions is still expensive, then the rate of development of deeper-water areas here is more attenuated, even though the reserves of newly discovered fields substantially exceed those of shallow-water and land areas (Table 2). Total oil and gas reserves as of the beginning of 2017 in Nigeria were estimated, respec-

tively, at 3.1 billion t and 3.5 trillion m^3; oil production for this period was 120 million t; gas, 7.2 billion m^3.

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